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Multidisciplinary approach to studying the formation and development of beach-ridge systems on non-tidal uplifting coasts in Estonia

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The coastal ridge–swale systems in the west Estonian archipelago (Röögu, Lõimastu) and on the northern coast (Juminda), where wave and wind-built ridges are separated from each other by wet depressions, contain the records on ancient shoreline positions, major storm events and forest fires. The results are based on cartographic analysis, ground-penetrating radar survey, coring and radiocarbon dating. Seaward tilted layers in lower parts of the ridges refer to storm scarps. Water level rise and acidic waters flowing from ridges favour the accumulation of *Sphagnum* peat in swales. The main soil-forming processes are podzolization on ridges and paludification in swales. The obtained results show a clear dependence of soil-forming conditions and development of peat layer on morphology and dimensions of landforms, character of parent material, vegetation type and groundwater table. Paludification will lead to a complete burial of the ridges under peat turning the areas to homogeneous bog landscape.

Introduction

Strandplains with shore-parallel beach ridges bordering the seas and large lakes are typical landscapes on all continents, occurring also in many places at the northern latitudes (Lichter 1997, Björk and Clemmensen 2004, Clemmensen *et al*. 2012, Scheffers *et al*. 2012). These landscapes are particularly widespread on the eastern (Estonia, Latvia, Lithuania) and southern coasts (Poland, Germany) of the Baltic Sea but also in Denmark and the southern part of Sweden. The ridge–swale systems of different age and at different stage of development are valuable landscapes for reconstructing histories of climatic changes and other major events during their formation and evolution. The coastal landforms (beach ridges with coastal dunes) in Estonia are unique because of the location in an area of tectonic land uplift, making it possible to examine nearly the whole sequence of the system in the Holocene timescale. Our study was focused on different environmental conditions and characteristics affecting the development of sandy coastal landscapes in order to understand the development history of the ridge–swale complexes. The ridge–swale systems provide records of sea-level fluctuations, ancient shoreline positions, major storm events, forest fires and periods of intensive aeolian accumulation,

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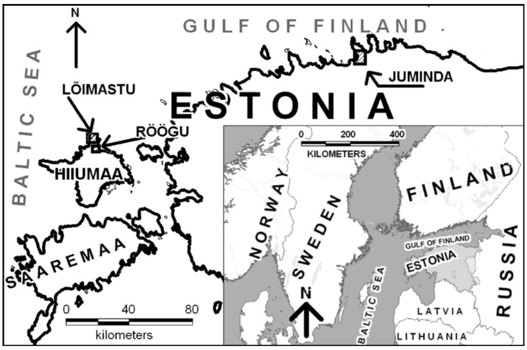

Fig. 1. Location of the study areas.

and also traces of human impacts. Many driving forces like waves, exposure, foreshore bathymetry, coastal plain gradient, longshore and cross-shore drift, sediment supply and calibre, groundwater table, coastal vegetation, and the like can be involved in the formation and dynamics of the system (Buynevich *et al*. 2004, Scheffers *et al*. 2012, Billy *et al*. 2014). Catastrophic events are expressed in both erosion and deposition records. Erosion surfaces, or scarp imprints, revealed in a cross section of beach deposits, might indicate storm or tsunami events (Tamura 2012). Due to the wave climate and sediment supply information archived in ridges they also offer an insight into storm activity during the postglacial coastal evolution (Shennan *et al*. 1999, Buynevich *et al*. 2004, Komatsubara *et al*. 2008, Scheffers *et al*. 2012).

The structure and properties of soils both on ridges and in swales reflect the later history in the evolution of these landscapes. Changes in local hydrography, water regime, nutrient supply, climatic changes, deposition conditions, and the like are usually reflected in soil profiles. The structure and properties of mineral soils on ridges combined with the character, properties and age of peat deposits in swales contain a lot of information about the environmental conditions and major events in the evolution of the landscape. Hence, the study focused on both the initial formation (mostly geological processes) of ridge–swale complexes as well as on the later stages of their development (e.g., formation of soil, podzolization, changes in vegetation, paludification of inter-ridge depressions) with the aim to examine the formation and evolution of the ridge–swale complexes of different age and at different locations in Estonia.

Study sites and geological background

Three study sites along the coast of Estonia were selected for the study — Lõimastu and Röögu on the island of Hiiumaa (well exposed to the Baltic Sea) and Juminda (exposed to the Gulf of Finland) on the mainland (Fig. 1). All the study sites are similar in geomorphology, soil and vegetation cover but different in topography and age. The Quaternary cover is represented by till and varved clay, which are overlain by sand and peat. The ancient coastal ridges are separated from each other by narrow wet depressions. Due to the location of the coastal zone of Estonia on the southern slope of Fennoscandian crystalline shield, which is subject to tectonic and isostatic land uplift, the whole area is emerging at the mean rate of 1–2.8 mm yr^{-1} (Vallner *et al*. 1988, Torim 2004, Kall *et al*. 2016). The regional Holocene sea level history is complicated due to glacio-isostatic processes. The post-glacial land uplift varied during different stages of the Baltic Sea. Just after deglaciation, the rate of crustal rebound was several times higher than today (Torim 2004, Kall *et al*. 2014). Concurrently with land uplift, the relative sea level during the past more than 8000 years was also strongly affected by the eustatic changes in the sea level (Eronen *et al*. 2001). After the transgressive phases of the Baltic Sea (max. 10 300 cal yr BP and 7800 cal yr BP), the shoreline retreated and the beach erosion was less intensive (Saarse *et al*. 2007, 2010, Saarse and Vassiljev 2010). As a result, less material was produced and deposited, hence the formed beach ridges are low (Raukas *et al*. 1994, Raukas 2011).

The Lõimastu study site is located on the northern coast of the Tahkuna Peninsula on the island of Hiiumaa. The area started to develop in the middle of the Limnea Stage (2500 cal yr BP) (Hyvärinen *et al*. 1988). The landscape profile is characterized by a single high dune ridge (up to 14.5 m a.s.l.) dividing the study profile into two parts. The ridge–swale topography, on which we focused in this study, is exhibited landward

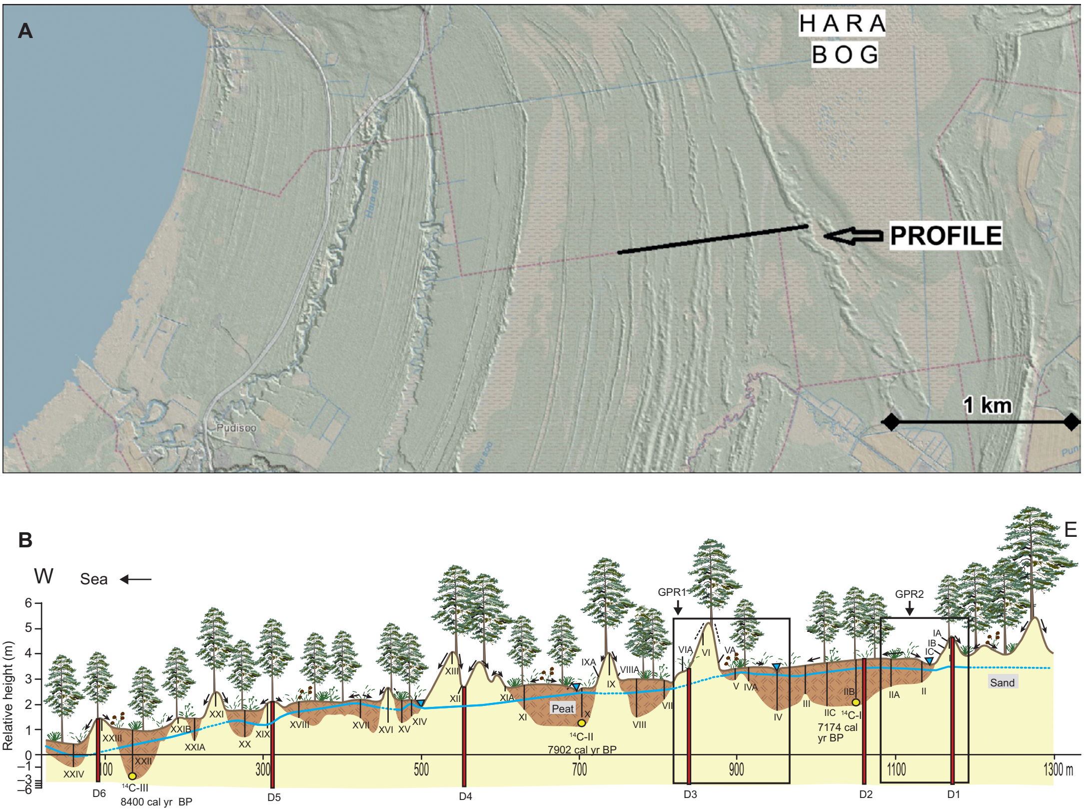

Fig. 2. Juminda study site. (**A**) Relief map based on LiDAR, and (**B**) landscape profile (location in Fig. 2A) based on coring and GPR results, where IA–XXIV mark peat cores and soil pits, D1–6 mark drill holes, ^{14}C (I–III) radiocarbon dates from basal peat (yellow circles). Water level is marked with the blue line, where the dotted line marks interpreted water level. Temporal waterbodies are marked with blue triangles. Black arrows show water movement on micro relief. GPR1 and GPR2 show ground-penetrating radar profile locations.

the high dune belt. The system of foredunes and dunes occurs at the seaside. The coastal formations are situated between 6.0–8.5 m a.s.l. The parallel long and narrow (10–50 m) sandy ridges are oriented from west to east. The mean relative height of the ridge crests varies from 0.5 to 1.0 m (max. up to 2 m). The peat layer in swales is relatively thin (0.2–0.7 m) (Vilumaa *et al*. 2013, Anderson *et al*. 2014).

The Röögu study site is located in the eastern part of Tahkuna Peninsula on the island of Hiiumaa, approx. 1 km from the sea. The development of this area started in the beginning of the Limnea Stage (3500 cal yr BP) (Hyvärinen *et al*. 1988). Today, the coastal formations are situated between 9.0 and 11.0 m a.s.l. The long and narrow (usually 10–70 m) sandy ridges are NW–SE oriented. The dimensions of the ridges at this site are comparable with those at the previous one: the swales are 25–125 m wide and the peat layer is 0.5–1.0 m thick (Vilumaa *et al*. 2013, Anderson *et al*. 2014).

The Juminda study site is located on the western coast of the Juminda Peninsula, ~4 km from the shoreline (Fig. 2A). This area emerged from the sea at the end of the Ancylus Stage (around 8400 cal yr BP) (Kessel and Raukas 1967, Björck 1995, Saarse *et al*. 2003, 2010). The coastal formations are situated between 24 and 28.5 m a.s.l. The ridges are 20 to 110 m wide and are N–S oriented. The coastal formations here are much higher than those on Hiiumaa: the heights of the ridge crests are 1–2 m. The paludified depressions are also wider (50–275 m) and the peat layer is thicker (0.7–2.0 m) than at the other study sites (Vilumaa *et al*. 2013).

Material and methods

The ridge–swale systems at the Hiiumaa and Juminda study sites were investigated along three landscape transects using several methods. The routes of the transects were selected according to the orientation and morphology of the landforms in order to cross the ridge–swale complexes in the direction perpendicular to the shorelines at the moment of their formation. We conducted topographic and ground-penetrating radar (GPR) survey along the transects, and used the LiDAR data from the Estonian Land Board to examine the topography and general features of the geological structure of the study sites. Sediment samples were taken from the boreholes and soil pits for granulometric analysis. Piezometric pipes were used to measure the water level in swales. The mineral soil profiles were studied in the soil pits dug on beach ridges. To assess the age of the landforms, we used the land-uplift curve (Torim 2004), the results of several earlier studies (Saarse *et al*. 2010) and the ^{14}C dating data from our earlier studies (Anderson *et al*. 2014, Vilumaa *et al*. 2016). Most of the data were acquired during the field work carried out from 2009 to 2015.

Ground-penetrating radar (GPR) survey

The internal stratification of the ridges was investigated using ground-penetrating radar SIR-3000 with a 100 MHz and 270 MHz transceiver. The GPR data processing was carried out using the Road Doctor and Radan 7 software. Several markers were recorded along the GPR profiles and their locations were fixed using Garmin 60 CSx GPS. Boreholes (up to 9 m deep) were drilled with engine-driven hand auger on the profiles in order to support the GPR survey with sedimentological and stratigraphical data. It also made it possible to calibrate the speed of electromagnetic waves (EMW) in various layers and to interpret the thickness of the layers (time-to-depth conversion). Coring was stopped in hard minerogenic deposits (till, gravel or varved clay) underlying the sand. In order to determine the exact thickness of layers (shown in figures), the radar wave velocities were calibrated using *in situ* drilling data. The GPR wave velocity is determined by factors such as grain size, porosity, changes in bulk density at stratigraphic interfaces and variations in water content at an interface (Gómez-Ortiz *et al*. 2010, Hede *et al*. 2013). The radar signal velocities between 0.07–0.085 m ns^{-1} for saturated sand were used for the time-to-depth conversion (Billy *et al*. 2014). For peat, an average value was 0.035–0.038 m ns^{-1}. Relatively low electromagnetic wave velocity values in sand were caused by high water content in the old beach formations.

Radiocarbon dating (^{14}C)

Due to the acidic environment, the beach ridges lack the fragments of marine mollusc and gastropod shells (common in beach sediments), which have been completely dissolved. Therefore, peat from swales was the best option for dating the age of deposits to provide an insight into the development of swales. The radiocarbon (^{14}C) dating in our study was based on 10 cores obtained from peat samples taken from inter-ridge depressions using a Russian peat corer with a 50 cm sample chamber. Around 5 cm thick bulk samples were taken from the base of the basal peat unit (immediately above the mineral substrate). The dating of the bulk samples was conducted in the radiocarbon dating laboratory of the Institute of Geology at Tallinn University of Technology using the standard liquid scintillation technique (Punning and Rajamäe 1993). The radiocarbon dates (^{14}C yr BP) were calibrated (cal yr BP) using the age calibration online program of OxCal ver. 4.2. All dates reported are expressed in calendar years before present. The botanical composition of peat was described from the cores in the field. In all cases the degree (percentage) of peat decomposition was determined macroscopically (according to Largin 1977).

Soil analysis

The soil samples were analysed in the Laboratory of the Department of Soil Science and Agrochemistry, The Estonian University of Life Sciences. One sample from topsoil and one from subsoil horizons were taken from every soil pit.

Organic carbon and total nitrogen contents were determined from the topsoil samples and pH was measured from both top- and subsoil samples. The content of carbon was fixed in relation to the content of humus. Humus content was determined by oxidizing with $K_2Cr_2O_7$. The content of nitrogen was determined using the Kjeldahl method, described in detail in Binkley and Vitousek (1989). Both parameters are expressed in grams per 100 grams of soil. The carbon/nitrogen ratio (C/N) as an indicator of trophicity of a site for plant growth was calculated from the measured results of carbon and nitrogen, respectively. pH (pH_{KCl}) was measured with an InLab® Expert Pro combined pH electrode with temperature probe (Mettler, Toledo) in dilution of 0.1 $N_{KCl.}$

Results

GPR profiles and geomorphology

In our previous studies (Vilumaa *et al*. 2012, 2013, 2016, Anderson *et al*. 2014) we described a number of features that can be found in the GPR images recorded at the Hiiumaa study sites. We found several ancient ridges containing seaward-dipping reflections and ridges without any visible interface. The ridges in different sections of the transects were with different size and distance between each other and some minor ridges were entirely buried under organic layer (Fig. 2B). Generally, it was possible to distinguish three types of reflections. The most deep and clearest visible signal reflection consisted of strong, continuous horizontal reflectors with a slightly wavy geometry. This was ground-truthed as varved clay surface, sometimes covered by thin gravel layer. Similar signal appeared also in the interface of peat and sand. Weaker and sometimes discontinuous reflectors appeared just after varved clay layers. These layers were seaward-dipping, representing coarser-grained sediments or heavy mineral concentrations. The last type was a discontinuous reflection from the topmost part of the ridges (with no peat-cover). Mostly without visible lamination, this could be considered a wind-transported (aeolian) sand.

According to the GPR reflection, the Lõimastu study site was characterized by larger ridges (1.5–2.3 m without peat layer) at the landward end, while smaller (0.5–1.0 m without peat layer) and more densely-located ridges were present in the seaward section of the transect. The average thickness of the sand layer was reduced (from 4 to less than 3 m) also in the seaward direction. The underlying varved clay was covered by gravel or coarse grained and medium sand. The pits dug in the ridges showed fine-grained sand slight dominance over medium sand in the top 1-m layer.

The Röögu study site, which is a bit older, was characterized by somewhat larger dimensions (1–2 m without peat layer) of the ridges but with more scattered location in the landscape. There were a number of ridges buried under the peat layer, which were visible only in the GPR images. However, it was rather difficult to locate clearly tilted layers in this study site. The granulometry of mineral soil profile was quite homogeneous. Fine-grained sand dominated over medium sand in the upper part (Vilumaa *et al*. 2012, 2013, Anderson *et al*. 2014).

The oldest site in Juminda was characterized by the largest ridges (~4 m without peat layer) in the landward section of the transect (Fig. 2B), while smaller and younger ridges were located seaward. The swales were also larger. We found only a few minor ridges buried under the peat in these swales (from ridge I to ridge VI; *see* Figs. 3 and 4). The upper parts of the ridges were mostly made up of 1.5–3.5 m thick layer of fine- and medium-grained sand. In larger ridges, the uppermost sand layers were underlained by about 1.5–2.0 m thick seaward tilted layers of coarser-grained sand and gravel (Figs. 3 and 4) followed by a layer of very fine and partly cemented sand, which was clearly visible in the GPR image. The basal radar facies (8–9 m from the surface) was characterized by strong continuous reflections and consisted of fine-grained sand with some silt particles. The Juminda GPR profile also revealed quite unique landward tilted layers in coarser-grained sand and gravel (Fig. 4).

Soils and vegetation

The soils were typical of acidic environment

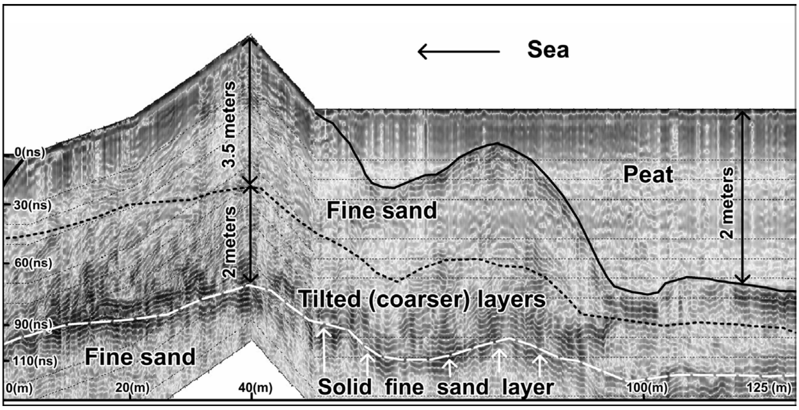

Fig. 3. GPR1 profile from the Juminda site. Peat, fine sand and tilted layers in coarser-grained sand can be clearly distinguished using GPR with 270 MHz antennae. For the location of the GPR profile *see* Fig. 2B.

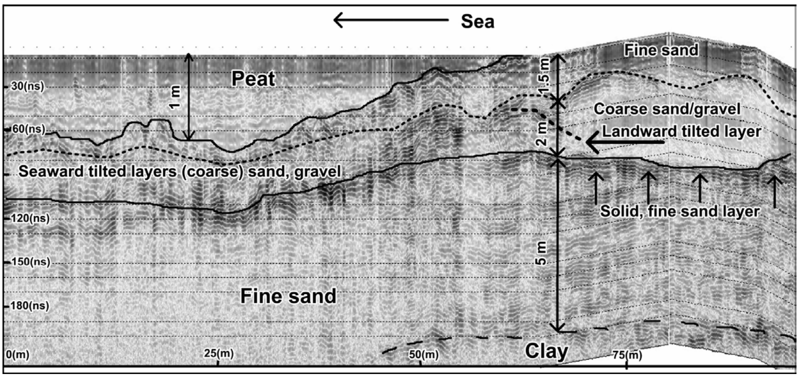

Fig. 4. GPR2 profile from the Juminda site. A landward tilted coarser-grained sand and gravel layer was found only in Juminda. Such features in nearly 9-m-thick sand formation might indicate extreme storm and high sea level events in the past. For the location of the GPR profile *see* Fig. 2B. As the vertical scale is changing due to very different elctromagnetic properties of different layers (dry sand, wet sand and peat), it is not shown in meters on the *y*-axis.

formed on marine and aeolian sands, and were similar in their physical and chemical properties at all the study sites. They can be divided into two major groups: (1) soils formed on the tops and slopes of beach ridges and (2) soils formed in swales. The main soil-forming process at higher elevations has been podzolization, which is one of the most obvious processes at the pedon scale on beach ridges and dunes (Reintam *et al*. 2001). Paludification has been predominant on the slopes of lower ridges and in the swale bottoms.

The soils of all the studied beach–ridge systems were formed on non-calcareous parent material, which is acidic, poor in nutrients and humus. The soil profiles were examined with regard to their topographic position. Typical sandy Haplic Podzols (L = PZ) occured on the crests of the beach ridges, alternating with sandy Spodic Gleysols (Arenic) (LG = GL) and Spodic Histic Gleysols (Arenic) (LG1 = GLhi) on the slopes and with Dystric Fibric Histosols (R) and Dystric Hemic Histosols (S = HS) in the inter-ridge depressions according to the system of the World Reference Base for Soil Resources (WRB) (Fig. 5). There was a strong mutual relationship between the properties of topsoil and the character of vegetation. Most of the ancient ridges were covered with boreal heath forest of the *Cladina* and *Calluna* types with Scotch pine (*Pinus sylvestris*) in the tree layer (Vilumaa *et al*. 2013). Some spruces and birches occurred in the undergrowth, especially in paludified swales. There was a well-developed dwarf shrub (e.g.,

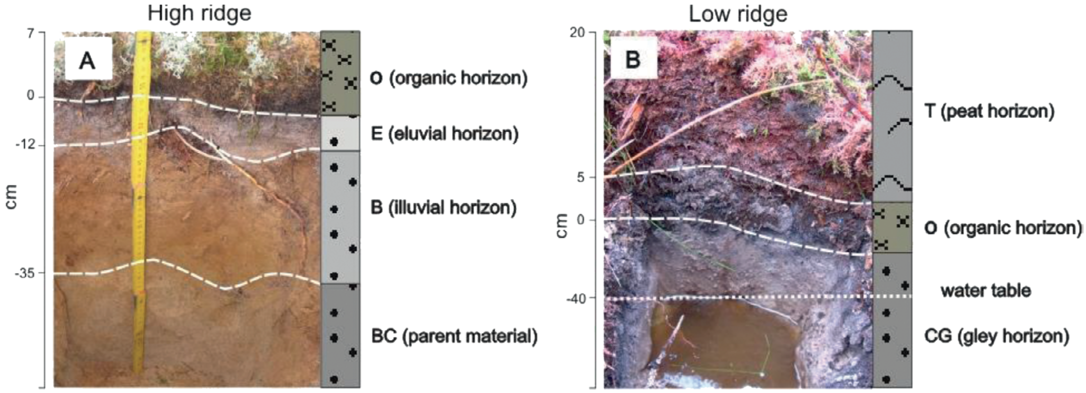

Fig. 5. Mineral soil profiles of (**A**) a high ridge and (**B**) a low ridge; 0 (cm) indicates the surface of mineral horizon.

Ledum palustre) and moss layer, which contained a considerable amount of *Sphagnum* spp.

There are three major genetic horizons in sandy Podzols: (O–(A)–E–B–C). It was common for all the study sites for the organic horizon (O) on the top to be relatively thin (3–10 cm). The organic horizon (litter) (O) was a bit thicker (10–20 cm) in the northern part of the Lõimastu study site. The eluvial horizon (E), which is rich in quartz, was relatively thin (up to 10 cm). The two uppermost horizons — O (2.5–3 pH_{KCl}) and E (2.5–3.5 pH_{KCl}) were more acidic than B-horizon (3.5–4.5 pH_{KCl}). The upper part of B-horizon (10–20 cm) was typically of dark brown colour and gradually turned into parent material at the depths of 40–50 cm. Quite often we saw very distinct transitions between eluvial and illuvial horizons in the soil profiles in both upper and lower parts of the ridges (Fig. 5). These distinct transitions were caused by finer-grained sediments in the lower parts of the soil profiles favouring quick accumulation of leached out substances from the upper horizons. It also indicates an active process of podzolization. A characteristic pattern of dark brown spots could be observed at the transition between B- and C-horizons. Those cemented particles (ortstein, hardpan) have been formed as a result of accumulation of aluminium, iron, manganese, and humus compounds from the overlying horizons. Down the profile, the pH values increased, exceeding 4.5 pH_{KCl} in the parent material (C). There were some very thin (1–3 cm), buried organic layers in sand in the northern part of the Lõimastu transect at depths of 25–50 cm. One of them was in the soil parent material of a ridge and the others were at the bottom of swales.

Spodic Gleysols (LG), Spodic Histic Gleysols (LG1), Dystric Fibric Histosols (R) and Dystric Hemic Histosols (S) are the most frequent soils in swales. Spodic Histic Gleysols were characterized by relatively thin topsoil (histic horizon) above the undifferentiated gley horizon. Spodic Histic Gleysols have been formed in the result of accumulation of both raw humus and peat. The soil profile usually consists of the following horizons: OT/T (< 30 cm), E-(Ea-), BCG (CG). Histosols with well-developed peat layer (30–100 cm) are classical mire soils (Kõlli *et al*. 2010). Spodic Gleysols and Spodic Histic Gleysols prevailed in the younger and seaward swales in Lõimastu. Histosols were found in the older, landward side of the transect. The swales in Röögu and Juminda were older and the peat layers were thicker: 50–70 cm in Röögu and over 1 m in Juminda. The character of Histosols in the swales of these study sites reflects the nutrition conditions.

The influence of tree species (pine, spruce and some deciduous species) on soil properties is seen in the topsoil C/N ratio (Köster and Kõlli 2013). The distribution of C/N ratio in organic soil horizons (O) at all the study sites was quite similar: 25–35 in Lõimastu, 25–45 in Röögu and 25–40 in Juminda. The C/N ratio in Histosols was higher in Juminda (30–50) and Röögu (35–45), while it was less variable (30–35) in Lõimastu.

Inter-ridge depressions and ^{14}C datings

The depressions of the study sites were characterized by vegetation dominated by moisture-tolerant plant species and anoxic soil conditions when flooded during rainy seasons and thaw in spring. The groundwater level between the ridges was high. Both temporal and permanent waterbodies existed there. The underlying varved clays prevent infiltration and soil water movement favouring paludification process. Coniferous trees (*Pinus sylvestris*) and dwarf shrubs growing on the ridges produce acidic litter. The water moving from the ridges to depressions was also acidic fostering the development of bog vegetation and ombrotrophic peat formation in swales. The vegetation in swales was represented by pine forests with *Ledum palustre* and *Sphagnum* spp. in the ground layer. Sporadic birch (*Betula pubescens*) and black alder (*Alnus glutinosa*) stands occurred in waterlogged swales. The development of the peat layer directly on non-calcareous sand was a common feature of all the study sites. Some differences appeared in the peat composition. In older areas, the lower parts of the peat profiles consisted of well decomposed (35%–50%) transitional fen-peat (*Lignetum, Lignetum–Carex*, *Lignetum* peat mixed with raw humus), the formation of which started (according to ^{14}C dating) 8400 cal yr BP (Juminda) and 1735 cal yr BP (Röögu). At the youngest study site (Lõimastu), the peat layer, which started to form 1386 cal yr BP was more variable. The upper parts of the peat cores were comparable with ombrotrophic bogs consisting of less decomposed (7%–20%) typical bog-peat (*Sphagnum*, *Eriophorum–Sphagnum* peat). There were some swales with temporal waterbodies with somewhat better nutrition conditions in Juminda, where the whole peat cores up to the surface consisted of fen- and transitional fen-peat (*Lignetum–Carex* and *Sphagnum*). At the youngest study site (Lõimastu), the peat layer was more variable. The mean thickness of peat between the ridges was only 30–40 cm. Unlike the other study sites, here we found samples of well decomposed (35%–50%) fen-peat (consisting of *Bryales*, *Phragmites*, *Carex*) covered with a thin layer of *Sphagnum*. At all the study sites, paludification has often started with wood peat (*Lignetum*) or wood–*Carex* (*Lignetum–Carex*) peat formation (Fig. 6A). Wood peat contained many charcoal layers (2–3 layers on average in one core), indicating frequent forest fires. The charcoal layers were generally very thin (1–2 cm), sometimes laying directly on sand.

Due to intensive growth of peat in swales, some of them were already filled by organic deposits and the bog vegetation has started to move onto the ridges. In the areas with smaller ridges, many of them were already covered with peat and cannot be identified in the landscape any longer.

Discussion

Coastal geology differs from the other disciplines of classical geology because of dealing with very rapid processes, which may take place in monthly, daily or even hourly scale. These processes reflect well the changes in climatic conditions or even the results of a single extreme event. Hence, we have carried out the GPR surveys in the selected three study sites along the transects with the aim of describing the processes that have led to the formation of the ridge–swale complexes in these areas.

We found a number of tilted layers on all the transects (very few in Röögu). Two types of such formations can be distinguished. Most of them are seaward-dipping reflections (Figs. 3 and 4) and can be found mostly in the basal parts of the ridges. As all the study sites are located on accumulative coasts, the formation of the tilted layers can be explained in the following way. The sand has been gradually eroded from a source area (e.g., tips of peninsulas and scarps visible on LiDAR image and Saarse *et al*. 2010), transported by sharp-angle-approaching waves along the shore in shallow sea conditions, and finally accumulated at the bay-head on the beach due to cross-shore drift. Continuous land uplift (2–2.8 mm yr^{-1}) in northern and western Estonia is supporting the process (Torim 2004, Saarse *et al*. 2010, Kall *et al*. 2016). Major storms or stormy periods cause temporary erosion in such locations. Fine-grained and lighter material is either eroded by waves and carried temporarily into the coastal sea or transported inland

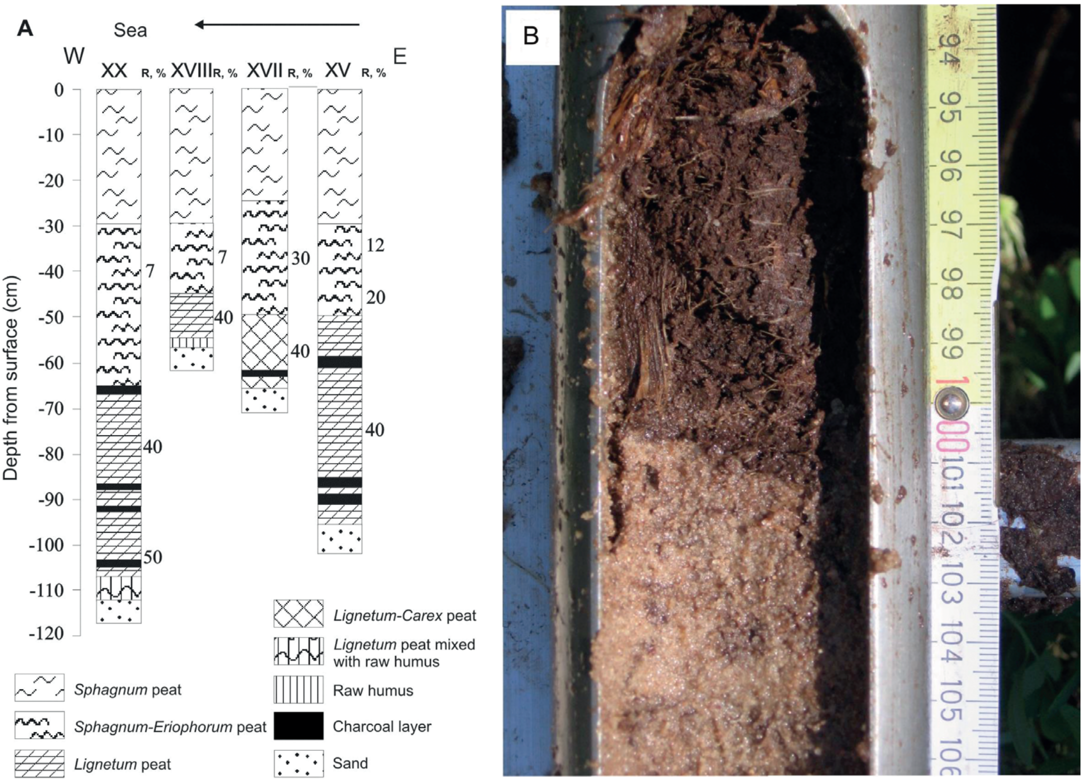

Fig. 6. (**A**) Peat profile from the Juminda study site, the numbers (7–50) next to the columns show peat decomposition rate (R, %). (**B**) A sharp interface between sand and peat deposits in Lõimastu.

by wind. Heavier minerals and coarser-grained sediments remain as a thin layer on the surface (Buynevich 2012), and will be covered by fresh deposits during the following calm period. Such layers with coarser-grained particles and concentration of heavy minerals are recognized as seaward-dipping reflections in geophysical records. Such layers of heavy minerals can be used as markers for spatial correlation of dune or ridge facies in reconstructions of coastal morphology and as proxies for sediment transport conditions (Buynevich *et al*. 2007a, 2007b). The sharp seaward-dipping reflections, high heavy mineral concentration and coarser grains in those layers represent storm scarps (periods of increased wind activity). Spacing of the scarps suggests a long-term recurrence of large-magnitude storms (Buynevich *et al*. 2007a, 2007b, Clemmensen and Nielsen 2010).

As high storm surges (up to 3 m) are characteristic for the eastern coast of the Baltic Sea (Tõnisson *et al*. 2016), we may assume that long seaward-dipping layers reaching higher elevations in larger ridges are probably formed during extreme events in high sea-level conditions. The eroded sediments were temporarily taken into the shallow coastal sea during these storms. After such events a lot of accumulated loose sand in shallow sea was available for building up large ridges. This material was gradually transported back onshore by waves and accumulated on top of erosional surface (long tilted layer), in form of high ridges by wind. But sooner or later, the depletion of loose sediment in the coastal waters limited the further growth of the ridges. On the other hand, short seaward-dipping layers mostly in smaller ridges are the indicators of smaller storms with lower sea-level. Most of the tops of the ridges (except in Röögu) were formed by aeolian accumulation of sand (aeolian caps). It is possible to distinguish the aeolian sand from marine one using GPR images. In general, aeolian processes play a significant role in covering or destroying beach ridge systems (Scheffers *et* *al.* 2012).

It is likely that nearly flat bottoms of the peat-filled depressions might indicate calmer wave activity periods when less sediment was eroded from the source areas and the amount of material for building up high ridges was limited.

We also found some landward-tilted layers in Juminda. This feature could be interpreted either as a landward-migrating shoreface bar or as washover deposits (Billy *et al.* 2014) indicating extreme storm events in very high sea-level conditions when coarser-grained sediments were washed across the ridges.

Some ridges are without seaward tilted layers (Vilumaa *et al.* 2013, Andersson *et al.* 2014). These were most likely formed as spits in the result of steady longshore sediment transport. Using GPR along such formations should reveal some layers reflecting the evolution process. Based on the LiDAR data and GPR profiles, we suggest that the highest ridge in Lõimastu was formed as a result of longshore sediment transport (Andersson *et al.* 2014). We have no clear explanation as to why the ridges in Röögu are almost without tilted layers. One reason might be a very homogeneous material. Another possibility is that the whole beach-ridge system was formed as a result of prevailing longshore sediment transport. This assumption is supported by the LiDAR image, showing the shape of those ridges.

Thickness of sand layers, dimensions of ridges and density of their location are also very important characteristics explaining the evolution process in the past. The described characteristics make it possible to analyse the changeability of sediment supply but also the geological structure of the studied regions, in general. Frequent occurrence of high ridges with tilted layers is probably an indicator of strong storms or stormy periods when a lot of deposits were intensively eroded from the feeding areas and transported to the study sites. High ridges with large depressions in between can be associated with rather calm periods with rare but extreme storms. Small ridges with narrow swales have been formed in calm periods (Vilumaa *et al.* 2016).

Finally, we discovered the landforms with increasing slope angles towards the sea in all the study sites. At the same time, the slope angle of the silt surface just below the sand layer is much smaller. We assume that this might be caused by decreasing sediment supply due to relatively calm weather conditions in the recent past (a couple of millennia). Such phenomena are usually associated with the availability of sediment and its transport regimes, exposure to the waves, sea level variation, and — to a lesser extent — with local sea-level history, neotectonic movements or glacio-isostatic rebound of the region. It is somewhat typical process for regressive sea (Linkrus 1988).

The next stages of development of the studied ridge–swale complexes are associated with vegetation and soil-forming processes and paludification of the inter-ridge depressions. The structure and properties of soils reflect more recent history in these landscapes. The obtained results show a clear dependence of soil conditions and the development of peat layer on morphology, dimensions of landforms, character of parent material, vegetation type and groundwater table.

The processes on beach ridges are characteristic of a rather stable system showing a steady evolution without major interruptions during the last couple of millennia. Only a few buried organic layers in sands indicate certain changes (either temporary changes in water regime or the beginning of aeolian accumulation) in the development of the local environment. The cool, humid climate, acidic parent material and litter produced by coniferous trees (Scotch pine) are favouring podzolization of the soils (Mokma *et al.* 2004). Soil-forming processes do not operate only in a vertical but also in a lateral direction due to additional lateral fluxes (Sommer *et al.* 2001). Lateral, inter-pedonal movement of solutions leads to the formation of soils differing by thickness of eluvial and illuvial horizons (Jankowski 2014). In all the study sites (mostly on ridges) dark brown ortstein (hardpan) layers are developing in B-horizon of the Podzols, indicating an intensive accumulation of iron and organic matter. The ortstein spots in earlier stages of formation get bigger in time and form a dense cemented layer that limits the water percolation and prevents the development of tree roots. Lower pH values might enhance the release of Fe and Al increasing the intensity of podzolization (Bogner *et al.* 2012). Thicker organic layers (O) were found in areas where groundwater level was closer to the surface. The share of deciduous plant species in the vegetation was much higher and the occurrence of gley horizon (G) indicated a high groundwater table and permanently wet conditions at these sites. The described soils are often located in areas where varved clays underlie the sands preventing infiltration and soil water movement. The obtained results show the pH values increase with the depth of soil layers at all the study sites. Lower pH values (3.5 in pH_{KCl}) in G-horizon in wet conditions as compared with those in C-horizon (4.0–4.5 in pH_{KCl}) at dry sites can be explained by the effect of acidic groundwater.

On the slopes of more complex morphology, small closed depressions act as geochemical traps, where compounds leached from the upper slope soils can accumulate. The peat layer of Histosols had much lower pH values (2.5–3.0) at all the study sites as compared with mineral subsoil layers, having a few higher peaks reaching up to 3.5 pH_{KCl}.

The C/N ratio in organic soil horizons was relatively high (25–45) at all the study sites. According to the classification of the forests in Estonia, Spodic Histic Gleysols in swales or on lower slopes of ridges have been formed under paludifying forests of the *Vaccinium uliginosum* site type (Paal and Leibak 2011, Köster and Kõlli 2013). Low productivity of these soils is due to acid and wet conditions, in which the activity of soil biota is inhibited and the nutrients are not released by the mineralization of organic matter. High C/N ratio in litter (> 20) means that the decomposition rate is low and nitrogen is one of the limiting nutrient for plant productivity. This results in the stagnation of organic matter flow throughout the ecosystem and further paludification of soil cover (Köster and Kõlli 2013). The litter on the soil surface was poor in calcium, magnesium, potassium and nitrogen but contained considerable amounts of iron, aluminum and silicon. As litter is poorly consumed by soil organisms, the accumulation of nitrogen was prohibited resulting in high values of C/N ratio (35–45). The soil organisms had very little impact also on the decomposition of litter and transition of organic matter.

The dynamics of the groundwater level and the character of water movement is one of the key factors in paludufication process of the inter-ridge swales. Our study sites reveal a very complicated nature of water regimes. The freshly formed ridges in regressive sea conditions shifted inland and started to overgrow with vegetation, which in turn was favoured by increasing humidity of climate. Moist inter-ridge areas were probably vegetated earlier (Käyhkö *et al*. 1999). The water movement was dependent on the orientation, height and width of the ridges. The coastal formations of larger dimensions acted as barriers for water flow. Also the shallow clay layers could play a foremost role in the hydrology as their presence affects the groundwater flow net (Gómez-Ortiz *et al*. 2010). Sometimes adjacent large raised bogs with steep slopes towards the ridge–swale complexes might affect their moisture conditions.

The irregular character of the age and thickness of peat layers like in Röögu and Juminda (Table 1), indicate a very complicated nature of surface water movement and groundwater level fluctuations. Temporary changes in local groundwater tables may be caused by forest fires. Gradual changes probably occurred due to land uplift. It is possible that the swales between older beach ridges at higher elevations remain wet for a longer period. There are some depressions with temporary waterbodies among drier swales during wet seasons even today, for instance in Lõimastu and Juminda. Considering the rate of tectonic land uplift in Lõimastu (2.5 mm yr^{-1}) and based on the comparison of the altitudes of the mineral surfaces of the swale bottoms with radiocarbon dating results of the basal peat layers in these swales, we can roughly conclude that the paludification process started about 1300 to 1600 years after the initial formation of the swales. This was also confirmed by the optically-stimulated luminescence (OSL) method (Vilumaa *et al*. 2016) dating the ridge to 2200 ± 120 years BP.

The ^{14}C dating results show that within the limits of a study site the development of peat layer between ridges was more dependent on the parameters of coastal formations and water movement than on the altitude and age of the ridge–swale complex. The oldest and deepest peat core (8400 cal yr BP) on seaward side of the Juminda profile and the altitudes of the ridge–swale system (24.0–28.5 m a.s.l.) show that the study area emerged from the sea more than 8400 years ago. According to Saarse *et al*. (2010), the larger ridges might have developed 9000–8900 cal yr BP. But there seems to be a correlation between the age of the area and the thickness of the peat layer. It suggests that in general the process of paludification in the older areas (Juminda, Röögu) started earlier and lasted longer than at the younger sites. The older study sites have mainly bog-peat and transitional fen-peat between the ridges. The presence of transitional fen-peat in lower peat cores shows a less acidic environment with more nutrients available for plants in earlier times. Deeper swales with temporal waterbodies have also had better nutrition conditions and transitional fen development stage has persisted longer. In smaller swales between lower ridges where peat layers are thinner, the process of paludification started later. In conditions of limited nutrient supply, the transitional fen stage was much shorter and was quickly replaced by the ombrotrophic bog stage. In the stage of transitional (mixotrophic) fen, the character of vegetation was highly variable and dependent on nutrients and moisture. In case of a thinner peat layer (the tree roots penetrate to mineral deposits) and dryer environment, the swales had been covered by forest. As the peat layer became thicker and the groundwater level higher, the growth conditions for trees worsened. The former forests turned to fens or transitional fens. In swales with better drainage, raised bogs started to develop without going through the stage of fen or transitional fen.

At all the investigated sites, the wood-peat has developed directly on sand (Fig. 6B) and contained a number of charcoal layers indicating frequent forest fires, which accelerated the development of mire landscape. There was a dependence between wood-peat layers and forest density in the past. Forest density is one important factor contributing to the extent of the fires (Kotilainen 2004). A faint charcoal horizon with only a small amount of charcoal, however, suggests that little vegetation and small amount of organic material was burned during the fire event(s) (Käyhkö *et al*. 1999). Fires usually have a minor long-term influence on vegetation succession in ombrotrophic peatlands. *Sphagnum* tends to recover rapidly (few decades) after the disturbance. Most fires are generally superficial burning the above-ground biomass without destroying the peat deposit, hence allowing the rapid recovery of conifers and ericaceous shrubs (Magnan *et al*. 2012). Sometimes stronger fire events (thicker charcoal layers) could be recognized in peat cores, which might cause a situation where thinner peat layer is older than the thicker peat layer. There is no universal dependence between the age and thickness of peat layer. Seasonally-low groundwater levels might create conditions for forest fires (Morris *et al*. 2015). Due to the low human impact on those areas, it is possible to assume that the forest fires were wild not human-induced fires. It is quite obvious that forest fires destroying the vegetation cover on sandy ridges trigger aeolian activity (Käyhkö *et al*. 1999, Kotilainen 2004, Matthews and Sep-

Table 1. Radiocarbon and calibrated dates of study sites (bulk samples).

Sample ID/lab no.	Site	Elevation (m a.s.l.)	Depth (cm)	Material dated	^{14}C date (yr BP)	Calibrated age (cal yr BP) 2σ	Model age (cal yr BP)	Transect part
Limnea Sea sites								
4/Tln-3501	Lõimastu	6.0	70–75	Peat	1501 ± 45	1518–1306	1386	Landward
13/Tln-3502	Lõimastu	7.0	65–69	Peat	1213 ± 50	1274–1003	1141	Middle
25/Tln-3503	Lõimastu	6.0	40–45	Peat	553 ± 50	652–510	581	Seaward
I/Tln-3506	Röögu	9.5	55–60	Peat	1066 ± 50	1123–804	981	Landward
V/Tln-3507	Röögu	10.0	80–85	Peat	1673 ± 50	1706–1418	1581	Middle
XIII/Tln-3508	Röögu	9.5	95–100	Peat	1801 ± 45	1865–1607	1735	Middle
XVIII/Tln-3509	Röögu	9.0	50–55	Peat	608 ± 45	661–540	601	Seaward
Ancylus Lake sites								
IIB/Tln-3515	Juminda	26.5	176–181	Peat	6247 ± 55	7274–6999	7174	Landward
X/Tln-3516	Juminda	26.0	140–145	Peat	7080 ± 55	8003–7794	7902	Middle
XXII/Tln-3517	Juminda	24.0	200–205	Peat	7595 ± 55	8539–8324	8400	Seaward

pälä 2014). We did not find any charcoal layers in the studied sandy ridges. Missing charcoal horizons in dunes and beach ridges may indicate that either the fire never reached the area or those layers were eroded due to deflation. Paludification is rather intensive today, and is going to continue in the future. This will lead to complete burial of the beach ridges and overall unification of that landscape.

As the areas have never been permanently populated, there are no signs of human settlements. Some traces of human activity (military forces) from the time when the study areas belonged to the Soviet Union border zone could be detected.

Conclusions

Using a variety of methods, we gathered new information on the structure, formation and development of the ancient ridge–swale landscapes. The landscapes with very low human impact have stored various signals about the natural processes and major events in the past.

The results of topographic- and GPR-surveys revealed a precise morphology and geological structure of all the study sites. A number of small ridges buried under peat were discovered. The GPR images showed certain sections in the profiles with both seaward and landward tilted layers giving valuable information on the formation conditions. Both seaward and landward tilted sediment layers in the ridges indicate their marine origin and the formation in the result of strong storms. We may conclude that long seaward-dipping layers in large ridges are signs of extreme storms accompanied by very high sea-levels while small ridges with similar thin layers are characteristic of calmer periods. The GPR images let us distinguish aeolian sands from marine ones. Our former attempts to differentiate these deposits by granulometry, mineral composition and texture were not successful enough.

Based on the altitudes of the basal parts of the ridges and considering the rates of tectonic and isostatic land uplift, the time of their formation could be roughly estimated. The botanical composition and the radiocarbon dating of the peat samples from the basal layers just above the mineral substrate made it possible to assess the beginning of paludification of the inter-ridge swales and the existing vegetation at that time. The paludification process at our study sites started at different times depending on the changes in groundwater tables and hydrological regimes. The nutrition conditions were much better and the species richness of vegetation much greater at the beginning of the process. Some swales had temporary waterbodies, which is reflected in higher pH and total nitrogen contents of the soils. The buried charcoal layers found in peat indicate later forest fires, which accelerated the paludification process. The accumulation of organic matter in such conditions turned the environment more acidic favouring the development of *Sphagnum* species. As a result, the lower ridges and lower slopes of higher ridges are covered with Spodic Gleysols and Spodic Histic Gleysols, which in the course of peat accumulation turn to Dystric Hemic Histosols and Dystric Fibric Histosols. At the same time podzolization is the main soil-forming process in the upper parts of the ridges. The process of paludification will lead to a complete burial of the ridges under peat in the future. The ridge–swale complexes will lose their heterogeneity and turn to homogeneous bog landscape.

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